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Analysis and synthesis of functional capabilities of monitoring systems of vehicle operation processes

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Abstract. Vehicle monitoring and operational management systems constitute a key component of modern transport infrastructure. The aim of this study was to analyse and systematise the functional capabilities of vehicle operational monitoring systems. The functional features of existing vehicle monitoring systems were examined, analysed, and synthesised. The systematisation of hardware configurations within these systems was conducted using morphological analysis. The analysis and synthesis of functional capabilities were performed through the systematisation of hardware configurations in existing monitoring systems. A generalised morphological formula for an integrated vehicle monitoring system was developed, comprising five core functional elements: operator monitoring tools; vehicle condition monitoring tools; vehicle monitoring tools; infrastructure interaction monitoring tools; and information analysis and utilisation tools for end users. This formula captured twenty morphological characteristics of these functional elements, as implemented in current monitoring systems. The synthesis of permissible morphological variants enables the construction of actual system configurations and facilitates the identification of the structure and functional potential of existing monitoring systems. Existing vehicle monitoring systems were identified, and their capabilities for monitoring vehicle operation were determined. Based on an analysis of the advantages and limitations of the systems under study, appropriate conditions for their application were established, along with the level of implementation of core monitoring functions, and the potential for developing both basic and diverse system components. The practical value of this research lies in providing guidelines for optimising the design and deployment of vehicle monitoring systems to enhance operational efficiency and safety

Keywords: control; registration of parameters; technical condition; hardware; morphological formula; systematisation

Introduction

Monitoring systems for vehicles and their operation processes are an integral part of modern transport infrastructure. They allow for constant monitoring of the technical condition of the vehicle, traffic parameters and resource consumption. This increases the level of traffic safety, reduces operating costs and increases the efficiency of fleet management. The main areas of application of monitoring are the technical condition of vehicles, traffic safety, economic efficiency, environmental aspects, fleet management. The main advantages of using monitoring are:

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reducing operating costs due to route optimisation and fuel economy; increasing repair intervals due to timely detection of defects; reducing the number of accidents; the ability to predict failures and plan maintenance; increasing transparency and controllability of transport enterprises. The main limitations for their intensive further development are: the need for significant initial investments in sensors, telematics and software; the need to protect data from unauthorised access; requirements for personnel qualifications; technical complexity of integration with existing transport systems, etc. The effectiveness of vehicle monitoring systems has been demonstrated across a wide range of sectors, from urban transport to international logistics. The implementation of such systems enables the simultaneous achievement of economic, technical, and social benefits (Cordoș *et al.*, 2025). As noted by V. Mateichyk & A. Navrotskyi (2024) further development of technologies (digital twins, big data, artificial intelligence) will further increase their effectiveness and ensure the transition to the concept of "intelligent transport". Therefore, the combination of tools and technologies in the appropriate hardware support for vehicle operation monitoring systems guarantees the most reliable information and ensures their effective operation in real conditions. V. Mateichyk & A. Navrotskyi have systematised the hardware support schemes of vehicle operation monitoring systems using the morphological analysis method. The morphological analysis method consists of decomposing the system into functional elements, determining the main morphological features on which the degree of achievement of the system's functioning goals depends, and identifying the options for their implementation. According to I.V. Khudiakov (2021) the combination of individual options for all morphological features of functional elements forms a new system with its own properties and ensures the search for the most rational system scheme. Functional elements, morphological features, and options for their implementation are conventionally depicted in the form of a morphological matrix, which allows to search for all possible alternatives to solve the problem and choose the most optimal solution. It is precisely because of this that it is possible to create different options for monitoring system configurations, evaluate their advantages and disadvantages, and choose the optimal solution for specific transport operating conditions.

In the work I.V. Khudiakov *et al.* (2021) monitoring systems for vehicles and operators are considered. Modern prospects are shown for their application. However, the issues of systematisation of schemes and justification of configurations of monitoring means in the conditions of vehicle operation require further development. S. Burlaka *et al.* (2024) examined diagnostic models of vehicles that establish causal relationships between the technical condition of components and measurable diagnostic signals, in particular through structural-causal and simulation-based models, which enable the assessment of complex systems without disassembly. The authors concluded that, for effective non-intrusive vehicle diagnostics, the most appropriate approach is the application of structural-causal and simulation models employing sensitive, unambiguous, and stable diagnostic parameters. Simultaneously the study of V. Migal *et al.* (2022) demonstrated that the effectiveness of vehicle diagnostics largely depends on the intellectual capabilities of the diagnostic operator, as well as their knowledge and experience. It outlines the stages of intelligent diagnostics, discusses the advantages and limitations of organoleptic methods, and provides recommendations for training and professional development aimed at the rapid and accurate identification of 70-90% of faults. L. Görne *et al.* (2022) investigated methods of efficient data pre-processing for remote vehicle diagnostics aimed at substantially reducing the volume of transmitted data without loss of essential information. They propose a pre-processing algorithm for CAN FD (Controller Area Network Flexible Data-rate) bus data prior to the application of standard compression algorithms (e.g., LZMA2), which enables improved compression performance and, consequently, enhances the efficiency of data transmission and subsequent analysis of large-scale diagnostic datasets in cloud or backend systems for further use in analytics and machine learning. E.T. Michailidis *et al.* (2025) reviewed the integration of OBD-II (On-Board Diagnostics) with machine learning, emphasising its application in predictive maintenance, emissions monitoring, driver behaviour analysis, anomaly detection, and vehicle cybersecurity. While OBD-II provides standardised access to diagnostic and performance data under EU regulatory frameworks, machine learning extends traditional reactive approaches by enabling failure prediction, real-time anomaly detection, and fuel efficiency optimisation. The work A. Sipos (2024) is devoted to the application of monitoring information complexes in transport. However, the issues of combining means and technologies into appropriate schemes of hardware support for vehicle operation monitoring systems require development. This is what guarantees the receipt of the most reliable information and ensures their effective operation in real conditions. According to the results of the analysis of recent publications, it can be stated that the issue of developing a method for systematising schemes of hardware support for existing systems for monitoring vehicle operation processes, taking into account their functional capabilities, remains relevant. Given the results of recent research in this area, it is necessary to take into account the most significant of them for the further development of this area. Further research involves combining tools and technologies into appropriate hardware schemes for vehicle operation monitoring systems, which guarantees the receipt of the most reliable information and ensures their effective operation in real conditions. Additionally, performing an analysis and synthesis of the functional capabilities of existing vehicle operation monitoring systems will allow determining the appropriate conditions for the use and development of such systems. The goal of the study was to analyse and synthesise the functional capabilities of existing systems for monitoring vehicle operation processes. To achieve the goal, the following tasks were solved in the article:

1) to form a generalised morphological formula for a complex system for monitoring vehicle operation processes;

2) to identify existing vehicle monitoring systems with the determination of their functional capabilities;

3) based on an analysis of the advantages and disadvantages of the studied systems, to determine the appropriate conditions for their practical use and development within the scope of the generalised morphological formula for a complex vehicle monitoring system.

Materials and Methods

The study used a set of materials and methods that ensured the construction of a generalised morphological model of vehicle technical condition monitoring systems and the determination of their functional capabilities. The basis for the formation of the methodological base was the actual data obtained from the hardware of real monitoring systems, in particular from ELM327 scanners, Launch diagnostic devices, Ruptela trackers, tachographs and remote diagnostics and technical condition prediction systems. In addition, technical documentation, descriptions of the functionality of sensor channels and information models used in the practice of operating motor vehicles were used. The key method of the study was morphological analysis, which allowed the decomposition of the monitoring system into five main functional components: means of controlling the operator's actions, means of controlling the technical condition of the vehicle, means of monitoring the cargo or object of transportation, means of interaction with the infrastructure and means of processing information to support user decision-making. For each component, a set of morphological features was determined – a total of twenty characteristics that reflect possible implementation options for system elements. Based on these features, a morphological matrix was constructed, which provided a systematisation of possible configurations of monitoring systems and justification of their application in various conditions. The morphological formula of the system was formed by step-by-step coding of functional elements with the assignment of designations of the type x_{11}, x_{41}, x_{51}, x_{61} in accordance with the type of data received, the method of their collection, transmission channels and analytical processing methods. The formula was constructed according to an algorithm that provided for the selection of basic functional elements, the establishment of options for their technical implementation, verification of the logical compatibility of the combined features and further analytical interpretation of the resulting configuration. Thus, it was possible to obtain a generalised description of the monitoring system, which allows comparing different hardware solutions by the level of their functional coverage.

To assess the functional capabilities of monitoring systems, methods of comparative analysis, evaluation and criterion comparison were used. The systems were analysed for completeness of coverage of morphological features, ability to provide accurate and relevant data on the technical condition of the vehicle, integration capabilities and suitability for use in real-world conditions. In particular, it was found that ELM327 provides the minimum permissible level of functionality, while Launch diagnostic complexes are characterised by much broader capabilities for collecting and analysing information. Verification of the constructed morphological model was carried out by analysing real operational data of vehicles. For this purpose, time series of parameters recorded during engine operation, data on operator actions, arrays of diagnostic codes of the OBD system, as well as information obtained through additional and infrastructure sensors were used. Comparison of real data with the results of morphological modeling confirmed the correctness of the formed structure and its compliance with the practical capabilities of various types of monitoring systems. The logic of the study involved the sequential execution of several stages: collection and classification of source data, isolation of morphological features, construction of a generalised system formula, evaluation of functional properties of various technical solutions and verification of the model on real operational data. The use of such a methodological approach allowed to obtain a comprehensive characteristic of monitoring systems, to identify promising directions of their modernisation and to form scientifically based recommendations on the choice of the optimal configuration of hardware for various operating conditions.

Results and Discussion

Formation of a generalised morphological formula for a complex system to monitor vehicle operation processes. For an effective combination of means and technologies in the corresponding schemes of hardware support of vehicle operation monitoring systems, it is necessary to guarantee the receipt of the most reliable information and ensure the effective operation of vehicles in real conditions. To ensure the flexibility of the process of forming certain monitoring systems and systematic research of vehicle operation processes, an approach to systematising the hardware support of such systems has been developed, presented in V. Mateichyk & A. Navrotskyi (2024). Five main functional elements have been identified in the complex monitoring system:

1) means of monitoring operators;

2) means of monitoring the technical condition of vehicles;

3) means of monitoring transportation facilities;

4) means of monitoring interaction with the infrastructure;

5) means of analysing and using information by the consumer.

Reflecting individual implementation options for 20 different morphological features of these functional elements, it is possible to form a large number of valid combinations of system configurations. This method ensures that the solution will always be unique, while each configuration has its own advantages and disadvantages to meet specific needs under given operating conditions. The generalised morphological formula for a complex monitoring system is:

$$\left[\begin{array}{c} \left(x_{14}(x_{11}, x_{12}, x_{13}); x_{23}(x_{21}, x_{22}); x_{32}(x_{31}, x_{33})\right) \\ + \begin{pmatrix} x_{41}(x_{42}, x_{43}, x_{44}); x_{51}(x_{52}, x_{53}, x_{54}); x_{61}(x_{62}, x_{63}); \\ x_{72}(x_{71}, x_{73}, x_{74}); x_{82}(x_{81}, x_{83}) \end{pmatrix} + \\ + \begin{pmatrix} x_{91}(x_{92}, x_{93}, x_{95}); x_{10\ 1}(x_{102}, x_{103}, x_{104}); \\ x_{111}(x_{112}, x_{113}, x_{114}); x_{121}(x_{122}, x_{123}, x_{124}) \end{pmatrix} \\ + \left(x_{134}; x_{143}; x_{154}\left((x_{152})\right); x_{163}(x_{161}, x_{164})\right) \\ + \left(x_{171}(x_{173}); x_{182}(x_{181}); x_{193}(x_{191}); x_{202}(x_{203})\right) \end{array}\right]. \tag{1}$$

The variable part of the first functional element of the operator monitoring tools (driver, etc.) (x_{14}) is statistical information (x_{11}), information about the person (x_{12}) and information of a reference nature (x_{13}). This information is obtained using special equipment in the external infrastructure environment (x_{23}) and is transmitted to the consumer (operator) in the form of information variants about external networks (x_{32}), which can be applied. This is the first component of the formula (1) solution of the problem. For the second functional element (1) of the considered variant N. Penna *et al.* (2001): information is obtained and has the form of working statistical information (x_{41}), with the variable part in the components: information about the vehicle (x_{42}), information of a reference nature (x_{43}), special information statistical information (x_{11}), information about the person (x_{12}) and information of a reference nature (x_{44}). According to the method of obtaining information is obtained as for a variety of formed/received information about the technical condition of the vehicle, obtained from standard sensors and systems (x_{51}), with a variable part in the components: additional vehicle sensors (x_{52}) – installed directly on the vehicle, engine and units, a combined version (x_{53}) – when combining standard and additional sensors into one information system, special equipment in the external infrastructure environment (x_{54}). The transmitted information has the form of statistical information (x_{61}), with a variable part in the components: information about the vehicle (x_{62}), information of a reference nature (x_{63}), special information (x_{64}). All information transmitted, according to the formula solution, is processed on a carrier outside the vehicle in the infrastructure environment (x_{72}) and transmitted using external information communication networks (x_{82}). For the implementation of the third functional element of the solution (1), the approaches described by S. Storm van Leeuwen *et al.* (2004), E. Krueger *et al.* (2005), and A. Holovan *et al.* (2019) are adopted. This element corresponds to a category of information that does not include data on the condition of objects transported by the vehicle (x_{91}). This may be a type of information about the state of objects transported by the vehicle, which is not transmitted (x_{101}) to the consumer. In addition, according to the method of obtaining information – it is not received from outside the vehicle (x_{111}) by the consumer. Also, according to the method of transmitting information, it is not transmitted outside the vehicle (x_{121}) into the surrounding environment. The fourth functional element of the formula solution (1) of the problem is implemented by considering the option Y. Bai (2016): for the type of information – for which information about the parameters of the infrastructure environment is obtained on the basis of information about the parameters of the infrastructure environment (x_{132}), with a variable part in the components: statistical information (x_{131}), reference information (x_{133}), special information (x_{134}). In terms of the means of obtaining and transmitting information about the parameters of the infrastructure environment, it is transmitted from the infrastructure (x_{143}), with a variable part in the components: by means of radio, video communications (x_{141}), from the vehicle itself (x_{142}), a combined option based on a combination of all the previously mentioned options (x_{144}). Also, according to the means of obtaining and transmitting information about the parameters of the infrastructure environment, it is transmitted using special equipment in the infrastructure environment (x_{154}), with a variable part in the components: standard sensors and systems (x_{151}), additional vehicle sensors (x_{152}), a combined option (x_{153}). In addition, according to the same feature, information is transmitted in the following way – using external communication networks (x_{163}), with a variable part in the components: cable connection (x_{161}), the use of gadgets (x_{162}) and (or) special equipment in the infrastructure environment (x_{164}). The fifth functional element of the formula solution (1) of the problem is implemented by considering an option for using means of analysis and the use of information by the consumer M. Kelller (2004) and S. Eggleston *et al.* (2006): which is stored in the following way – on an external medium in an external infrastructure environment (x_{172}), for a sufficiently long observation time (x_{182}). Moreover, the level of processing of the received information for the formation of the corresponding monitoring base – has the form of structured and unstructured information. Also, the means of analysis and use of information by the consumer in terms of the level of information processing – are adapted for use by computer systems (x_{193}) of the observer (consumer, technical supervision bodies, etc.). And in terms of the level of use – they are used for control in general and/or for individual parameters of the vehicle (x_{202}), with a variable part in the components: for diagnosing the condition (x_{203}), for determining indicators of the operational efficiency of the vehicle and/or individual units (x_{205}), for predicting the condition parameters (x_{206}), for forming combined (integrated) indicators of operation (x_{207}).

Identification of existing vehicle monitoring systems. Here are some individual structural options for the hardware of existing monitoring systems for studying vehicle operation processes. ELM 327 scanner-adapter. The morphological formula of the monitoring system based on ELM 327 has the form:

$$\begin{bmatrix} \left(x_{41}(x_{42},x_{43},x_{44});x_{51}(x_{54});x_{61}(x_{62},x_{63});x_{72}(x_{71});x_{82}(x_{81},x_{83})\right)+ \\ +(x_{143};x_{154}((x_{151}));x_{163})+(x_{172}(x_{171});x_{182}(x_{181});x_{193};x_{202}(x_{203},x_{205},x_{207})) \end{bmatrix}. \quad (2)$$

The ELM327 scanner-adapter is designed for self-diagnosis (by the operator, driver, etc.) of a vehicle by connecting to the OBD-II diagnostic connector, reading and clearing error codes, as well as real-time monitoring of various engine parameters and other systems. It works in conjunction with a smartphone or computer via Bluetooth or Wi-Fi, displaying data through special applications such as Torque, allowing car owners to independently detect and eliminate malfunctions without contacting a car service. The system provides comprehensive troubleshooting capabilities, enabling the reading of error codes from electronic control units and their subsequent clearance. It supports real-time monitoring through the display of key engine operating parameters, including engine speed, vehicle speed, fuel consumption, coolant temperature, sensor readings, and other data, depending on the specific vehicle configuration and installed software. In addition, the device may function as an on-board computer, allowing trip-related data to be tracked and stored. Certain models offer configurable settings, permitting adjustments to selected parameters, such as smoothing engine temperature indicators for steady driving conditions or activating service-related functions. Furthermore, vehicle identification is supported through the reading of the vehicle identification number (VIN) and the assessment of system readiness for diagnostic procedures. This vehicle diagnostic adapter is characterised by a relatively low cost and offers several advantages, including affordability, versatility, ease of use, broad compatibility with various vehicle models and user devices, and support for self-diagnostic functions. However, a number of limitations should also be noted. These include comparatively low build quality and durability, potential connectivity issues with certain vehicle models, limited or absent iOS support in earlier versions, the risk of overheating during operation, and possible vulnerabilities related to data security. The device is advisable to use for self-diagnosis of the car by connecting to the OBD-II connector and reading data from electronic systems using smartphone applications such as Torque or OBD Car Doctor. The adapter is compatible with most cars manufactured after 1996 (USA) and 2001 (Europe), allows to detect errors, monitor parameters in real time (fuel consumption, engine temperature), build graphs and even delete errors, which makes it a convenient and economical tool for car owners. Of the studied and analysed tools, this option is not complete from the point of view of covering the functionality in the generalised morphological formula (1) of the monitoring system. Not all functional elements of formula (1) in the presented system have sufficient development in the basic and varied components. This option is one of the least developed: the first and third functional elements are not covered, the implementation options for the second, fourth and fifth functional elements are limited.

Launch diagnostic device. The morphological formula of the Launch-based monitoring system has the form:

$$\begin{bmatrix} \left(x_{41}(x_{42},x_{43},x_{44});x_{51}(x_{54});x_{61}(x_{62},x_{63});x_{72}(x_{71});x_{82}(x_{81},x_{83})\right)+ \\ +(x_{143};x_{154}((x_{151}));x_{163}) \\ +(x_{172}(x_{171});x_{182}(x_{181});x_{193};x_{202}(x_{201},x_{203},x_{204},x_{205},x_{206},x_{207})) \end{bmatrix}. \quad (3)$$

Launch diagnostic devices are multibrand scanners and tools for computer diagnostics of cars, performing a wide range of functions, including reading and erasing error codes, viewing parameters in real time, performing service functions (coding, adaptation, actuator tests), as well as diagnosing all electronic systems of the car. These devices exhibit considerable variation in functionality, ranging from compact standalone units to advanced Android-based tablets that support modern communication protocols such as DoIP (Diagnostics over Internet Protocol) and CAN FD. Their functional scope typically includes comprehensive diagnostics of vehicle systems, encompassing the engine, transmission, ABS, airbags, immobiliser, and other electronic control units. They enable the reading and clearing of diagnostic trouble codes (DTCs) and support real-time data visualisation by displaying system parameters in both numerical and graphical formats. In addition, many devices provide access to specialised service functions, including control unit adaptation and coding, service interval resetting, and actuator testing. A further characteristic is broad multi-brand compatibility, with support for approximately 150-200 vehicle manufacturers across European, American, and Asian markets. Selected models also incorporate intelligent diagnostic features, such as automated VIN reading and system readiness assessment. Launch diagnostic devices are characterised by a high level of functionality and broad vehicle coverage, combined with an intuitive user interface and access to online support services. At the same time, certain limitations should be noted, including relatively high acquisition costs and the need for regular software updates to maintain full operational capability. The use of Launch diagnostic devices is considered most appropriate in professional automotive workshops, where comprehensive diagnostic, coding, programming, and adaptation procedures for electronic vehicle systems are required. These systems include, but are not limited to, the engine, transmission, ABS, and airbag control units. The devices enable the reading and clearing of error codes, real-time monitoring of system parameters, testing of actuators, and the execution of service-specific functions, such as key coding, diesel particulate filter (DPF) regeneration, and electronic parking brake (EPB) maintenance. This option is incomplete from the point of view of covering the functionality in the generalised morphological formula (1) of the monitoring system. Not all functional elements of formula (1) in the presented system have sufficient development in the basic and varied components. The first, third and fourth functional elements should be attributed to the uncovered functional elements. The second and fifth functional elements can be attributed to the insufficiently developed in this option. Although the fifth functional element has the greatest prospects in the development of diagnostics and forecasting of the technical condition of the vehicle.

Ruptela tracker (Ruptela FM-Tco4 HCV/HCV 3G). The morphological formula of the monitoring system based on the Ruptela tracker has the form:

$$\left[\begin{array}{c} (x_{14}(x_{11},x_{12},x_{13});x_{23}(x_{21},x_{22});x_{32}) \\ +\begin{pmatrix} x_{41}(x_{42},x_{43},x_{44});x_{51}(x_{52},x_{53},x_{54});x_{61}(x_{62},x_{63}); \\ x_{72}(x_{71},x_{73},x_{74});x_{82}(x_{81},x_{83}) \end{pmatrix}+ \\ +\begin{pmatrix} x_{91}(x_{92},x_{93},x_{95});x_{10\ 1}(x_{10\ 2},x_{10\ 3},x_{10\ 4}); \\ x_{11\ 1}(x_{11\ 2},x_{11\ 3},x_{11\ 4});x_{121}(x_{122},x_{123},x_{124}) \end{pmatrix} \\ +(x_{134};x_{143};x_{154}((x_{152}));x_{163}(x_{161},x_{164})) \\ +(x_{171}(x_{173});x_{182}(x_{181});x_{193}(x_{191});x_{202}(x_{203})) \end{array}\right]. \qquad (4)$$

The Ruptela tracker is a satellite-based vehicle monitoring device that determines the location of the vehicle and transmits data to the monitoring system in real time. Ruptela devices are characterised by a reliable design, can have internal and external antennas, and are also equipped with backup batteries and functions for driver control and vehicle safety. Ruptela tracking devices provide a comprehensive set of functional capabilities for vehicle monitoring applications. The devices determine precise vehicle coordinates using GPS technology and transmit this information to a remote server for processing within the monitoring system. Data transmission is performed via cellular communication networks, while an integrated backup battery ensures continued operation for several hours in the event of a primary power supply failure. The devices support a wide range of interfaces, including 1-Wire and RS232, as well as digital and analogue inputs and outputs. Selected models additionally incorporate driving style analysis, driver identification, and fleet management functionalities. Continuous monitoring of GSM signal quality is supported, and certain configurations allow remote ignition immobilisation to enhance vehicle security. The advantages of Ruptela trackers are primarily associated with their reliability and advanced fleet management capabilities. The hardware is designed to operate under harsh conditions, with enclosures resistant to moisture, mechanical shock, and extreme temperatures. The systems enable real-time fleet monitoring, contributing to improved operational efficiency through detailed supervision of vehicle movement and status. Fuel consumption control is supported through the monitoring of fuel levels and usage patterns, which facilitates the prevention of fuel theft and the optimisation of consumption. Driving behaviour analytics, including the detection of harsh braking, rapid acceleration, and speeding events, support improvements in road safety and reductions in vehicle wear. In addition, monitoring of equipment operation allows the tracking of operating time, work cycles, and other performance indicators, which is particularly relevant for specialised vehicles and machinery. The systems also enhance theft protection by providing accurate location data to support rapid response in the event of vehicle or cargo theft. Furthermore, Ruptela offers specialised solutions tailored to the requirements of various sectors, including logistics, construction, and agriculture. Despite these advantages, several limitations should be considered. Ruptela solutions are positioned in the premium segment, resulting in relatively high equipment and service costs compared with less sophisticated alternatives. The configuration and integration of complex system architectures require the involvement of qualified personnel with appropriate technical expertise. In addition, system performance is dependent on the availability of stable mobile network coverage, which may be limited in certain regions. Ongoing software maintenance and regular updates are also required to ensure reliable operation, increasing the overall demands on system administration. The appropriate conditions for using the Ruptela tracker include installation on commercial vehicles (trucks, special equipment) for accurate location tracking, fuel consumption control, vehicle condition monitoring and cargo safety, which allows to optimise logistics and prevent abuse. Of the studied and analysed means, this option is relatively complete from the point of view of covering the functionality in the generalised morphological formula (1) of the monitoring system. However, not all functional elements of formula (1) in the presented system have sufficient development in the basic and varied components. The first and fifth functional elements have the possibility of further development of the basic components without sufficient development of the varied components.

Tachograph. The morphological formula of the monitoring system based on the tachograph has the form:

$$\left[\begin{matrix} \left(x_{14}(x_{11},x_{12},x_{13});x_{23};x_{32}(x_{31},x_{33})\right) \\ +\begin{pmatrix} x_{41}(x_{42},x_{44});x_{51};x_{61}(x_{62},x_{63},x_{64}); \\ x_{72}(x_{71});x_{82}(x_{81},x_{83}) \end{pmatrix}+ \\ +(x_{91};x_{10\ 1};x_{11\ 1};x_{121}) \\ +(x_{134};x_{143}(x_{142});x_{154}((x_{152}));x_{163}(x_{161},x_{164})) \\ +(x_{171}(x_{172},x_{173});x_{182}(x_{181});x_{193}(x_{191},x_{192},x_{194});x_{202}(x_{203},x_{207})) \end{matrix}\right]. \quad (5)$$

A tachograph is an on-board monitoring device that records and stores data on the movement of a vehicle, as well as the driver's work and rest schedule, including the vehicle's speed, distance traveled, and working hours. Its main task is to ensure road safety by preventing driver fatigue and monitoring compliance with the rules, as well as increasing overall transportation safety. The primary purpose of a tachograph is to support the monitoring of vehicle operators through the recording of drivers' working and rest periods, thereby contributing to the prevention of fatigue, which is recognised as a significant factor in road accidents. In addition, tachographs facilitate compliance with traffic regulations by enabling the monitoring of vehicle speed and other driving parameters, helping to prevent speeding violations and associated penalties. Their use also contributes to enhanced road safety, particularly in the context of commercial freight and passenger transportation. From an organisational perspective, tachographs enable companies to monitor driver activity and operational performance, supporting the optimisation of transport processes. Functionally, tachographs provide continuous data recording by capturing and storing information on vehicle speed, distance travelled, working day start and end times, rest periods, and other traffic-related parameters. Driver identification is ensured through the use of dedicated driver cards, which allow personal data to be securely recorded. The devices support encrypted data storage within internal memory and, in the case of modern tachographs, data transmission to remote servers via integrated GPRS communication modules. Information is made accessible through built-in displays for on-screen visualisation, while thermal printing mechanisms enable the generation of hard-copy records when required. The use of tachographs offers several advantages, including improved road safety, enhanced control over driver activity and fuel usage, route optimisation, and the provision of legally valid evidence for dispute resolution and regulatory compliance. However, certain limitations must also be acknowledged. These include additional costs associated with device installation and maintenance, as well as the need to adhere to strict operational regulations, which may impose constraints on drivers' working schedules. Expedient conditions of use: it is advisable to use the tachograph on trucks with a gross weight of more than 3.5 tons and buses carrying more than 8 passengers for commercial transportation. It is also needed for regular paid transportation outside the settlement, even if the weight of the vehicle is less than 3.5 tons. This option is incomplete from the point of view of the coverage of the functionality in the generalised morphological formula (1) of the monitoring system. Not all functional elements of formula (1) in the presented system have sufficient development in the basic and varied components. The first, third and fifth functional elements can be attributed to the insufficiently developed in this option. They can mostly be implemented partially in the basic components and varied components.

System of remote monitoring and forecasting of the technical condition of the vehicle KhNADU TESA. Morphological formula of the monitoring system based on the system of remote monitoring and forecasting of the technical condition of the vehicle KhNADU TESA:

$$\left[\begin{matrix} \begin{pmatrix} x_{41}(x_{42},x_{43},x_{44});x_{51}(x_{52},x_{53},x_{54});x_{61}(x_{62},x_{63},x_{64}); \\ x_{72}(x_{71},x_{73},x_{74});x_{82}(x_{81},x_{83}) \end{pmatrix}+ \\ +\begin{pmatrix} x_{91}(x_{92},x_{93},x_{94},x_{95});x_{10\ 1}(x_{10\ 2},x_{10\ 3},x_{10\ 4}); \\ x_{11\ 1}(x_{11\ 2},x_{11\ 3},x_{11\ 4},x_{11\ 4});x_{121}(x_{122},x_{123},x_{124}) \end{pmatrix} \\ +(x_{132}(x_{131},x_{133},x_{134});x_{143}(x_{141},x_{142},x_{144}); \\ x_{154}((x_{151},x_{152},x_{153}));x_{163}(x_{161},x_{162},x_{164})) \\ +(x_{172}(x_{171},x_{173},x_{174});x_{182}(x_{181},x_{183}); \\ x_{193}(x_{191},x_{192},x_{194});x_{202}(x_{201},x_{203},x_{204},x_{205},x_{206},x_{207})) \end{matrix}\right]. \quad (6)$$

KhNADU TESA is a satellite monitoring system for rolling stock, which is a specialised software and hardware complex for managing commercial operation and technical operation at small motor transport enterprises. The system is founded on the concept of integrating into a unified complex, first, the full range of tasks currently faced by transport systems from both infrastructural and vehicle-related perspectives, and second, the coordinated actions required to address these tasks. It is intended to support the operational needs of small motor transport enterprises by optimising fleet performance and represents a comprehensive solution for diagnostics, control, monitoring, and life-cycle management at the vehicle operation stage. Structurally, the KhNADU TESA system comprises a telematics server with dedicated software, BN-Complex™ telematics server software, a GIS-based telematics server, and core application modules, including the "Virtual Mechanic" and "Service Fuel Eco NTU-HADI-12" software packages. In addition, the system incorporates subscriber terminals that enable data acquisition, transmission, and interaction with the central infrastructure. The functional capabilities of the KhNADU TESA system are organised into three principal groups: monitoring functions, management (control) functions, and functions related to information storage and integration with external communication networks. The monitoring functions of the KhNADU TESA system provide continuous automated determination of vehicle navigation parameters and assessment of vehicle status based on data received from telematics receivers and control sensors. These functions include monitoring the activation of sound and light signalling systems, the position of a dump truck body, the operation of attached and auxiliary equipment, temperature conditions, instances of exceeding permissible driving speeds, and fluid levels in vehicle tanks. Navigation and operational data are automatically transmitted to the enterprise at predefined time intervals, while emergency messages are generated and transmitted in response to changes in vehicle status parameters detected by sensors or control devices. In the event of external communication channel failure, navigation and status data are automatically recorded in non-volatile memory and subsequently transmitted once communication is restored. The system also supports automated monitoring of vehicle routes and schedules, generating emergency notifications in cases of deviation. Real-time tracking of selected vehicle units is enabled, accompanied by graphical visualisation of vehicle locations and parameters on vector-based electronic maps, tabular representation of location and status data, and the display of emergency alerts at the enterprise in the form of alarm windows with warning signals. The management functions of the KhNADU TESA system include the formation of control zones on electronic maps to supervise vehicle movement, as well as the control and analysis of actual vehicle mileage over specified time intervals. The system enables the transmission of dispatcher commands to vehicle actuators and supports voice communication between enterprise dispatchers, the server, and vehicle operators. All actions performed by operators are automatically logged in an event register, ensuring traceability and accountability of operational activities. Functions related to information storage and integration with external networks are implemented through the centralised storage of data in a unified database. The system provides conversion of information into formats compatible with user networks, supports data exchange with external information systems, and enables the creation of databases structured in accordance with user-defined archival formats.

The KhNADU TESA system demonstrates a number of significant advantages. It provides continuous automated monitoring of vehicle movement processes, including the assessment of operating conditions, route duration, and compliance with work schedules, as well as real-time visualisation of vehicle locations and routes on electronic maps. The system also ensures continuous automated control of technical condition parameters and preventive and corrective maintenance modes, enabling the evaluation of vehicle reliability and fuel and energy efficiency. Additional advantages include high message delivery efficiency, full confidentiality of processed and transmitted data, compatibility with cartographic information systems, and the capability to integrate customised software modules developed to address specific user requirements. Furthermore, the system is characterised by relatively low equipment costs and minimal operational expenses. At the same time, certain limitations must be acknowledged. These primarily relate to additional costs associated with the installation and maintenance of system components, as well as the requirement to comply with strict operational and maintenance regulations for life-support and monitoring subsystems responsible for supervising operator activities. With regard to conditions of use, client workstations may be deployed both within the enterprise's local network and externally via Internet-based connections. In cases where only periodic monitoring of vehicle activity is required, simplified dispatcher centre configurations can be connected to the telematics server using web technologies. In addition, the KhNADU TESA transport and telematics system is capable of integration into the architecture of intelligent transport systems. Based on the analysis of the examined solutions, this system provides a comprehensive level of functional coverage with respect to the generalised morphological formula (1) of the monitoring system. All functional elements defined by formula (1) are implemented through basic and variable components, with the exception of the first functional element related to operator monitoring. This element can be partially realised through basic components, without the development of corresponding variable components.

System of remote control and forecasting of the technical condition of the vehicle and the condition of the operators CMV. Morphological formula of the monitoring system based on the system of remote monitoring and forecasting of the technical condition of the vehicle and the condition of the operators CMV:

$$\begin{bmatrix} (x_{14}(x_{11},x_{12},x_{13});x_{23}(x_{21},x_{22});x_{32}) \\ +\begin{pmatrix} x_{41}(x_{42},x_{43},x_{44});x_{51}(x_{52},x_{53},x_{54});x_{61}(x_{62},x_{63}); \\ x_{72}(x_{71},x_{73},x_{74});x_{82}(x_{81},x_{83}) \end{pmatrix}+ \\ +\begin{pmatrix} x_{91}(x_{92},x_{93},x_{95});x_{10\ 1}(x_{10\ 2},x_{10\ 3},x_{10\ 4}); \\ x_{11\ 1}(x_{11\ 2},x_{11\ 3},x_{11\ 4});x_{121}(x_{122},x_{123},x_{124}) \end{pmatrix} \\ +(x_{134};x_{143};x_{154}((x_{152}));x_{163}(x_{161},x_{164})) \\ +(x_{171}(x_{173});x_{182}(x_{181});x_{193}(x_{191});x_{202}(x_{203})) \end{bmatrix}. \tag{7}$$

CMV works similarly to the KhNADU TESA system, only with the possibility of deep monitoring of the operators' condition. Advantages and disadvantages: similar to the KhNADU TESA system, only with the possibility of deep monitoring of the operators' condition. Expedient conditions of use: similar to the KhNADU TESA system, only with the possibility of deep monitoring of the operators' condition. Of the studied and analysed means, this option is the most complete from the position of covering the functionality in the generalised morphological formula (1) of the monitoring system. All functional elements of formula (1) in the presented system have development in basic and varied components. A summary of the study of the functional capabilities of existing systems for monitoring vehicle operation processes is shown in Table 1.

Table 1. Generalisation of the functional capabilities of studied vehicle operation monitoring systems

No.	Studied vehicle operation monitoring systems	Functional capabilities of studied vehicle operation monitoring systems				
		Receiving and transmitting information about operators	Receiving and transmitting information about vehicle technical condition	Receiving and transmitting information about the status of transportation objects	Receiving and transmitting information about the parameters of the infrastructure environment	Analysis and use of information by the consumer
1	ELM 327	–	– +	–	– +	– +
2	Launch	–	– +	–	–	– +
3	Ruptela FM-Tco4 HCV/HCV 3G	– +	+	+	+	– +
4	Tachograph	– +	+	– +	+	– +
5	KhNADU TESA	– +	+	+	+	+
6	CMV	+	+	+	+	+

Note: "–" – does not correspond; "+" – corresponds; "– +" – partially corresponds

Source: calculated per data from the Official website of the State Statistics Service of Ukraine (n.d.)

Table 1 demonstrated significant variation in the functional coverage of the analysed vehicle operation monitoring systems. Basic diagnostic solutions, such as ELM 327 and Launch, provide only partial support for selected functional elements, whereas integrated telematics platforms, including Ruptela FM-Tco4, tachographs, and KhNADU TESA, ensure broader functional implementation. The most comprehensive coverage is observed for the CMV system, which fully satisfies all functional elements of the generalised morphological model, while KhNADU TESA demonstrates near-complete coverage with a partial limitation in operator monitoring functionality. Figure 1 showed the working graphs of changes in vehicle parameters during diagnostics in a separate mode.

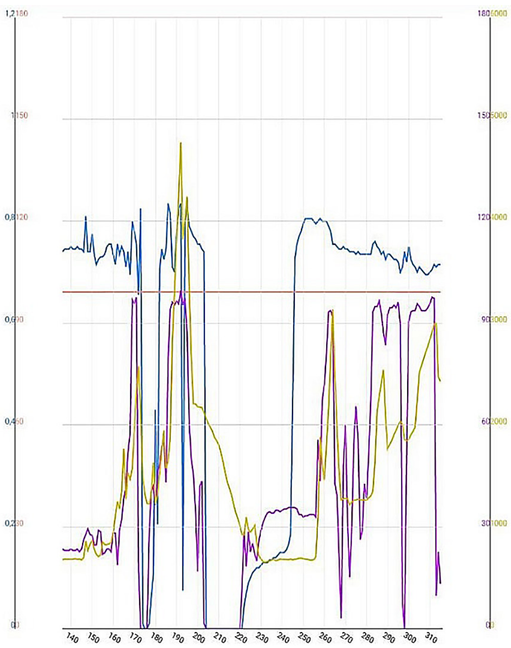

Figure 1. Working graphs of changes in vehicle parameters during the diagnosis process

Note: 1 – lambda probe 2, voltage 0.715V; 2 – lambda probe 2, short-term mixture adaptation; 3 – normalised load value; 4 – engine speed (max. engine speed 2428 min-[1])

Source: developed by the authors

Figure 1 illustrated the dynamic behaviour of key engine parameters during the diagnostic process. Fluctuations in lambda probe voltage and short-term fuel mixture adaptation indicate active regulation of the air-fuel mixture in response to changing engine load and operating conditions. The observed variations in normalised load and engine speed, reaching a maximum of 2428 min^{-1}, reflect transient operating modes, confirming the responsiveness of the engine management system during diagnostics. Overall, the application of the morphological approach enabled the development of an optimised intelligent vehicle diagnostic system configuration by identifying key functional parameters and integrating heterogeneous diagnostic and telematics tools into a unified decision support framework, thereby enhancing monitoring efficiency, diagnostic depth, long-term observation capabilities, and early fault detection in accordance with existing research findings. Previous research, notably by I.V. Khudiakov *et al.* (2021), primarily addressed the structural and informational aspects of developing vehicle monitoring systems, yet it did not fully explore the integration of various classes of diagnostic equipment into a unified model. In contrast, the work by Y. Yao *et al.* (2015) focused on organising data flows and constructing information and analytical systems, but it did not employ morphological analysis as a formalised method for selecting model parameters. Particular attention should be given to the comparison of the results of this study with the findings presented by M. Kacmarik & D. Fojtik (2023), which highlight the importance of integrating telematics systems with traditional diagnostic methods. However, in contrast to these approaches, the proposed model facilitates the integration of multiple tools for different purposes within a single decision support system, thereby enhancing its functional capabilities. In the work by K.-P. Schwarz (2000), modern vehicle monitoring systems are discussed; however, the selection and systematisation of their application schemes are not addressed. D.A. Roozemond (1999) investigated the applicability of autonomous intelligent agents in urban traffic control, proposing an agent-based model in which distributed intelligent agents adaptively respond to real-time traffic conditions to optimise signal control at intersections. The study demonstrated how such agent-based urban traffic control systems can improve responsiveness and intersection capacity compared with conventional traffic management approaches. T. Schüler (2001) investigated the use of GPS technologies for scientific purposes, particularly in climatology and meteorology. The study focuses on the precise measurement of tropospheric delays, which are critical for estimating atmospheric water vapour content and, consequently, for improving climate models and weather forecasting. In addition, the work examines the integration of GPS-derived data with numerical weather prediction models in order to enhance estimation accuracy and support advances in both fields. M.M. Atia *et al.* (2015) presented an autonomous indoor navigation system for ground vehicles that integrates inertial sensors, LiDAR, WLAN RSS, odometry, and floor maps to address position initialisation and self-alignment in GNSS-denied environments. By combining extended Kalman filtering with LiDAR-based positioning and heading estimation algorithms, the system achieves sub-metre positioning accuracy, as demonstrated through experiments conducted in a real indoor environment, confirming the effectiveness of multi-sensor data fusion for enhanced navigation performance. Thus, the results of the study confirm the effectiveness of using morphological analysis as a methodological basis for building the supporting structure of the diagnostic system, and also demonstrate the prospects of the developed model for use in intelligent transport systems. Comparison with previous scientific developments shows that the proposed approach has a higher level of structural flexibility, the ability to scale and integrate additional analysis modules, which ensures its competitiveness and scientific novelty.

Conclusions

During the study, an analysis and synthesis of the functional capabilities of existing vehicle operation monitoring systems were conducted using the morphological analysis method, which was employed to systematise the hardware architectures of such systems. A generalised morphological formula for a complex vehicle monitoring system was developed, consisting of five main functional elements: monitoring of operators, monitoring of vehicle technical condition, monitoring of transportation objects, monitoring of interaction with infrastructure, and the analysis and use of information by the consumer. The formula incorporates 20 morphological features of these functional elements, as implemented in existing systems. The synthesis of valid combinations of these morphological features enables the formation of feasible system configurations and identification of the structure and functional capabilities of current monitoring systems. The study identified existing vehicle monitoring systems, including the ELM 327 scanner-adapter, Launch diagnostic device, Ruptela tracker (Ruptela FM-Tco4 HCV/HCV 3G), tachograph, and the KhNADU TESA and CMV remote control and forecasting systems for vehicle and operator condition. Their functional capabilities for monitoring vehicle operation processes were evaluated. Based on the analysis of the advantages and disadvantages of these systems, the conditions for their appropriate use, the degree of implementation of basic monitoring functions, and the potential for further development of core and auxiliary components were determined. The analysis of the obtained results demonstrated that the model facilitates the integration of diverse data channels and their unification within a single decision support system. This approach enhanced the accuracy of technical condition assessments and ensures early detection of deviations, a conclusion that is corroborated by the consistency of the results with data from other studies presented in the paper. A comparison of the results with previous scientific works highlighted several common and distinct aspects. Future research will focus on developing models for the interaction of information components within vehicle operation monitoring systems, as well as decision-making algorithms within intelligent diagnostic frameworks.

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Conflict of Interest

None.

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Аналіз та синтез функціональних можливостей систем моніторингу процесів експлуатації транспортних засобів

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Анотація. Системи моніторингу та управління експлуатацією транспортних засобів є ключовим компонентом сучасної транспортної інфраструктури. Метою цього дослідження було проаналізувати та систематизувати функціональні можливості систем моніторингу експлуатації транспортних засобів. Було досліджено, проаналізовано та синтезовано функціональні характеристики існуючих систем моніторингу транспортних засобів. Систематизація апаратних конфігурацій у цих системах була проведена за допомогою морфологічного аналізу. Аналіз і синтез функціональних можливостей здійснено через систематизацію апаратних конфігурацій у наявних системах моніторингу. Була розроблена узагальнена морфологічна формула для інтегрованої системи моніторингу транспортних засобів, яка складається з п'яти основних функціональних елементів: засоби моніторингу операторів; засоби моніторингу технічного стану транспортних засобів; засоби моніторингу транспортних засобів; засоби моніторингу взаємодії з інфраструктурою; та засоби аналізу та використання інформації кінцевими користувачами. Формула охопила двадцять морфологічних характеристик цих функціональних елементів, що реалізовані в існуючих системах моніторингу. Синтез допустимих морфологічних варіантів дозволяє побудувати фактичні конфігурації систем і сприяє визначенню структури та функціонального потенціалу існуючих систем моніторингу. Було ідентифіковано існуючі системи моніторингу транспортних засобів, та визначені їхні можливості для моніторингу процесів експлуатації транспортних засобів. На основі аналізу переваг і обмежень досліджених систем були визначені відповідні умови їх застосування, рівень реалізації основних функцій моніторингу, а також потенціал для розвитку як основних, так і різноманітних компонентів систем. Практична цінність цього дослідження полягає у наданні рекомендацій для оптимізації проектування та впровадження систем моніторингу транспортних засобів з метою підвищення ефективності та безпеки експлуатації

Ключові слова: управління; реєстрація параметрів; технічний стан; апаратне забезпечення; морфологічна формула; систематизація